

# Feasibility of using Low-Cost COTS Sensors for Particulate Monitoring in Space Missions

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Real-time measurement of particles suspended in the spacecraft cabin is of great importance to verify that maximum allowable dust concentrations are not exceeded. This is primarily to protect astronaut health, but also has implications for dust-sensitive equipment. Recently, there is growing interest in low-cost commercial off-the-shelf (COTS) particle sensors by air quality researchers for their ability to map concentrations of airborne particulate matter in various terrestrial settings. In addition to low cost (< \$2,000), the compact size and minimal weight of these sensors make them a potential choice for space missions. The detection mechanism for these aerosol sensors is typically measurement of light scattered by particles as they flow through a sensing volume. The amount of scattered light for detection depends on the particle size, shape, density, and refractive index of the particle material. Ideally, particle instruments should be calibrated with reference instruments for each different type of aerosol measurement. In this study we review multiple parameters that may impact the performance of state-of-the-art low-cost aerosol sensors. Environmental factors such as temperature, relative humidity, low ambient pressure, radiation and charge environment, partial-gravity and microgravity can affect the accuracy of particle measurements. Characteristics of the dust aerosols including particle size distribution, aerosol composition, refractive index, morphology and concentration levels also affect the measurement accuracy. Finally, we look at these parameters and issues with respect to an example COTS low-cost aerosol sensor. Instrument performance specifications are evaluated, and experiments are performed to measure real-time concentrations of Arizona Road Dust (a terrestrial reference test dust) and lunar dust simulatant in a laboratory chamber. Overall, this study provides insight for evaluating spacecraft particulate monitoring technologies and raises questions to be answered before incorporating low-cost COTS sensors in future space missions to dusty destinations.

## Nomenclature

<i>ARD</i>	=	Arizona road dust
<i>APM</i>	=	Airborne Particulate Monitor (ISS payload experiment instrument)
<i>COTS</i>	=	commercial-off-the-shelf
<i>EVA</i>	=	extra vehicular activity

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<i>HEPA</i>	=	High Efficiency Particulate Air [filter]
<i>IoT</i>	=	Internet of Things
<i>ISS</i>	=	International Space Station
<i>LHS-ID</i>	=	Lunar Highlands Simulant
<i>OEM</i>	=	Original Equipment Manufacturer
<i>OPC</i>	=	Optical particle counter
<i>PM</i>	=	airborne particulate matter
<i>PM<sub>2.5</sub></i>	=	airborne particulate matter with an aerodynamic diameter finer than 2.5 $\mu\text{m}$
<i>PM<sub>10</sub></i>	=	airborne particulate matter with an aerodynamic diameter finer than 10 $\mu\text{m}$
<i>PSD</i>	=	particle size distribution
<i>RH</i>	=	relative humidity
<i>RI</i>	=	refractive index
<i>SWaP</i>	=	Size, Weight and Power
<i>SBIR</i>	=	Small Business Innovation Research

## I. Introduction

### A. Monitoring suspended dust in spacecraft cabins and habitats

Control of airborne dust suspended inside extra-terrestrial cabin spaces is an important priority for healthy, breathable air during space missions. Monitoring goes hand-in-hand with controlling airborne particulate matter, because the airborne debris must be quantified in real-time to determine whether maximum concentration requirements are met. The new NASA lunar exploration mission Artemis supports return of humans to the Moon and establishment of sustainable celestial habitats with construction of a lunar base. The repeated episodic exposures of astronauts to lunar dust must be controlled by a HEPA-level filtration system. The suspended dust poses a serious health threat to the crew and deleteriously impacts operation of electronics equipment and thermal surfaces.<sup>1-3</sup> During Apollo missions, suspended lunar dust was ubiquitous inside the lander and was shed from tools, sample containers and spacesuits. Once the dust entered the cabin, it was further lofted due to human activities or natural transport by the electrostatic fields, with visible contamination as well as large particle concentrations that were undetectable by the human eye.<sup>4</sup> There was no ability to quantify the airborne dust on the Apollo missions and no guidance on the health implications. Since then, NASA has developed requirements for the maximum allowable mass concentrations of both cabin dust and lunar dust are outlined in NASA Standard 3001 Volume 2, Rev B,<sup>5</sup> which states in paragraph 6.4.4.1:

“The system shall limit the cabin particulate matter concentration for total dust to  $<3 \text{ mg/m}^3$ , and the respirable fraction of the total dust  $<2.5 \mu\text{m}$  in aerodynamic diameter to  $<1 \text{ mg/m}^3$ .”

For lunar dust, a separate requirement 6.4.4.2 states:

“The system shall limit the levels of *lunar dust* particles less than  $10 \mu\text{m}$  in size in the habitable atmosphere below a time-weighted average of  $0.3 \text{ mg/m}^3$  during intermittent daily exposure periods that may persist up to 6 months in duration.”

Airborne particulate matter (PM) with an aerodynamic diameter of  $10 \mu\text{m}$  and smaller ( $\text{PM}_{10}$ ) is a concern because these sizes can be inhaled.  $\text{PM}_{2.5}$  cabin dust is specified separately because these sizes can go deeper into the lungs. Additional guidance for the short lunar lander sorties allows an average  $\text{PM}_{10}$  mass concentration of  $1.6 \text{ mg/m}^3$  for a 7-day surface mission.

### B. History of Low-cost Aerosol Sensors

Instrumentation for measuring airborne dust concentrations has matured significantly since the Apollo era. Large bench-top instruments for laboratory aerosol research were perfected over the decades and eventually miniaturization of these instruments became a priority. Personal monitoring options (including wearables) were needed for workers in hazardous occupations, such as coal mining, and atmospheric aerosol research required compact form and low power instruments for use on tethered balloons and drones. These smaller sensors are now part of the Internet of Things (IoT) in ‘smart cities,’ which incorporate networked environmental monitors for gaseous and aerosol pollution to inform citizens and improve community health by awareness.<sup>6</sup> They have been used to validate aerosol dispersion models in both environmental and occupational settings.<sup>7-8</sup> Some efforts sought to shrink reference-quality aerosol

instruments,<sup>9</sup> but now, there are small raw sensor components available in the \$5 to \$400 price range, which are considered original equipment manufacturer (OEM) parts. Some weigh as little as 30 grams with dimensions 4 cm x 4 cm x 2 cm, so they can easily be integrated into a system to create a commercial off-the-shelf (COTS) device that measures particles. This paper differentiates OEM (bare) components from COTS low-cost sensors, which are the final consumer-ready products. The OEM components rely on particles scattering light and fall into two categories: nephelometers or optical particle counters (OPCs). Nephelometers have a sensing chamber where a ‘cloud’ of particles all scatter light at once, which is picked up by a photodetector and correlated to particle mass concentration, a technique known as ensemble scattering. OPCs focus the aerosol entering the inlet into a single particle stream and record the pulse of light scattered by each individual particle, which is correlated to particle size and subsequently the number of pulses are summed and binned to give a particle size distribution (PSD). The key word in these descriptions of both nephelometers and OPCs is that the output is ‘**correlated**’ to particle mass concentration or particle size. By definition, nephelometers are not able to provide any particle size information. One example of a widely used OEM nephelometer is the Plantower<sup>TM</sup>.<sup>10</sup> Unfortunately this unit gives data output for PM<sub>2.5</sub> and PM<sub>10</sub> mass concentrations, which is questionable marketing.

In the literature, air quality sensors/instruments are generally considered ‘low-cost’ if they are \$2000 or less.<sup>11-12</sup> Availability and use of low-cost sensors for estimating the mass concentration of the airborne fine particulate matter has dramatically increased over the years, however, some are more accurate than others, and many performance evaluations and side-by-side comparisons are in published in the aerosol literature and by regulatory agencies such as the South Coast Air Quality Monitoring District.<sup>12-16</sup> One should note that the low-cost detection of airborne particles is not limited to light scattering-based techniques. As an example, Priyamvada et al., (2021) designed a miniature-sized portable device to sample aerosols (including bioaerosols) using electrostatic forces on substrate plates.<sup>17</sup> When operated with an ionizer and a precipitation electric field as low as 8 kV/cm, this device was able to collect more than 50% of particulate matter (PM) ranging between 0.1 to 10  $\mu\text{m}$ .

The compact, lightweight attributes of these low-cost COTS sensors along with simplicity of their operation make them a potential option for monitoring the airborne mass concentration of suspended PM inside space stations, vehicles, and habitats. The goal of this paper is to identify parameters that can affect the performance and accuracy of low-cost aerosol sensors in the lunar mission environment and to demonstrate that OEM sensors must be enhanced with physics-based data processing algorithms to provide more reliable measurements.

### C. Low-cost COTS Particle Monitors vs. NASA Requirements

Inexpensive particle monitors based on optical detection methods are ubiquitous, but can they really measure mass concentration and thus be used to address the NASA requirements mentioned above? Further, can these devices technically measure PM<sub>2.5</sub> and PM<sub>10</sub>? One of the main problems in this commercial space is the lack of transparency concerning the assumptions that are built into the conversion of scattered light to particle size and particle mass. Physics-based models used for this purpose are critical to the effective use and adoption of lower-cost PM sensing technologies across deployment domains in which direct, reference-quality, mass-based detection instruments cannot compete.

The primary motivation for considering small COTS devices to meet NASA requirements is project cost and lead time to flight certification, which also boils down to cost. Performance can be considered secondary when there are trades for reference-quality vs. reasonably good measurement data. Choosing a reference-quality instrument for mass concentration measurements for a crew vehicle destined to lunar orbit or surface missions is simply not practical because of large size, weight, and power (SWaP), not to mention complexity, maintenance needs, and consumables. For example, a reasonably good miniaturized alternative sensor, whether it costs \$100 or \$10,000, would take much less work to space-qualify and multiples can be sent on a mission for redundancy. That choice may overtake the need for reference-quality data. In addition to conducting and funding directed research and development of miniaturized aerosol monitoring technology through Small Business Innovation Research (SBIR) and other contract mechanisms, NASA subject matter experts and external collaborators are actively, continually watching the COTS aerosol realm for potential new developments. If there is any way for NASA to adopt COTS monitors, it may save money and years of development vs. in-house sensor projects. Naturally, there are tradeoffs. The downside to a hasty selection of a COTS monitor vs. selecting and further developing a promising new technology is potential loss of real-time insight into characteristics of aerosols that could impact crew health. Whether or not a COTS particulate monitor is considered for a future ISS technology demonstration at some point, the ultimate goal is to have multiple instrument options that are space-qualified for future NASA missions, as well as for commercial vehicles and habitats that are being developed

in the new low-Earth orbit economy. Particle monitors that have low SWaP are desirable for future distributed measurement systems, which will provide more granular spatial data, redundancy, and will enable future autonomous vehicles to sense and remedy air quality anomalies.

## **II. Environmental parameters impacting low-cost sensor performance**

Since most low-cost COTS particle sensors detect particles by single- or multiple-particle photometry/nephelometry,<sup>18</sup> they operate based on light scattering properties of the suspended PM which does not depend on gravity. This offers a big advantage for dust monitoring in space cabins as the Artemis mission includes a lander segment in lunar gravity (1/6 of Earth gravity), and the orbiter, similar to ISS, will have a low-gravity environment.

The International Space Station orbits Earth at an altitude of more than 300 km under high vacuum, microgravity, extremes of temperature, meteoroids, space debris, ionospheric plasma, and ultraviolet and ionizing radiation. The pressure inside the ISS is regulated to 14.7 psi (1 atm) and is equilibrated after docking and before hatch opening.<sup>19</sup> However, for the lunar lander, lower pressure environments are preferred, to reduce the number of hours necessary for pre-breathing (purging the body of nitrogen to avoid decompression sickness) and achieve more extravehicular activities (EVA) per mission.<sup>20-21</sup> This also reduces vehicle weight, which translates into fuel savings for the mission. For instance, the Apollo spacecraft were pressurized to only 5 psi (0.34 atm), but had a pure oxygen environment.<sup>22</sup> To study the impact of low air pressure on performance of the low-cost aerosol sensors, Li et al. (2020) conducted a 7-month continuous sampling campaign of PM<sub>2.5</sub> at an elevation of 1,534 m above sea level over Mountain Tai in China, which corresponds to an atmospheric pressure of 84.2 kPa (12.2 psi).<sup>23</sup> They observed minimal impact on accuracy from the reduced air pressure during their sampling campaign. However, Feinberg et al., (2018) established a 7-month-long campaign of performance evaluation of low-cost PM sensors in the cold, dry, and high-altitude climate of Denver, CO.<sup>24</sup> Their results show that different geographic location, meteorology, and aerosol properties can vary the average sensor accuracy drastically. Other studies have used OEM raw sensor components for high altitude studies without further adaptation or calibration.<sup>25</sup>

The crew compartment of the ISS is regulated to have an average temperature of 22±1°C and 40% RH,<sup>5</sup> which is about the same as that in typical terrestrial indoor settings. Some COTS low-cost sensors demonstrated good performance in ambient temperatures as low as 1°C when tested by Carotenuto et al., 2020 in the arctic environment.<sup>26</sup> Jayaratne et al., 2020 performed a sensitivity analysis for the effects of temperature while detecting a controlled concentration for six COTS low-cost sensors and their results revealed that the performance of these sensors is not significantly affected by increases in the ambient temperature up to 45°C; and increases in the relative humidity (RH) up to 75%.<sup>27</sup> Above this relative humidity, suspended particles undergo hygroscopic growth leading to overestimation of the mass concentration. One should note that the hygroscopic growth of the airborne particles is a function of the ambient dew point temperature, and Malings et al., (2020) conducted experiments with PM<sub>2.5</sub> monitoring and developed an equation to correct mass concentration estimates for temperature and RH.<sup>28</sup> This is not likely necessary for nominal operation because space vehicles and habitats will be designed for human comfort and avoid these extremes.

Another environmental factor of concern is that extra-terrestrial dust carries significant amount of charge due to direct exposure to the solar radiation,<sup>29-30</sup> which affects their airborne transport dynamics.<sup>4, 31-32</sup> This may cause losses within a particulate monitor if particles adhere to the inlet and the internal channels or flow path resulting in underestimation of dust concentrations. If the optics in the sensing volume are contaminated by the electrostatic adhesion of dust, readings from a low-cost sensor may be permanently compromised. Even on Earth, it is difficult to disassemble, clean and re-calibrate a low-cost sensor, considering the ease of replacement. Space missions must avoid consumables where possible, so a candidate low-cost sensor should be designed to minimize the potential for contamination, which will improve longevity and robustness.

## **III. Dust characteristics impacting the low-cost sensor performance**

The COTS low-cost sensors require initial calibration for the aerosol they are expected to measure, using gravimetric samples and/or mass concentration reference-quality instruments. The PSD of the airborne particles and

refractive index (RI) of the particle material are two major characteristics of suspended dust that can substantially impact the accuracy of the sensors.<sup>33-34</sup> Calibration of the sensor with a dust type that has a substantially different RI can result in significant over-estimation of PM mass if the RI of sampled dust exceeds that of the calibration dust and vice versa. By weight, 20% of lunar regolith consists of particulate matter finer than 20  $\mu\text{m}$  with sharp, irregular-shaped, abrasive grains.<sup>35</sup> The mode size of lunar dust sampled during Apollo 11 and 17 missions is shown to be between 100 and 200 nm.<sup>35-36</sup> A significant limitation of low-cost aerosol sensors that rely on light scattering is that they are unable to detect and measure particles less than 0.3  $\mu\text{m}$ ,<sup>37</sup> and thus will underestimate suspended PM if there is a large fraction of finer particles. Furthermore, suspended dust particles in this size range adhere to nearly everything with which they impact,<sup>38-39</sup> so they may be lost to walls and surfaces by high ventilation rates or grow by agglomeration, which both contribute to the uncertainty of the measured concentrations. Considering the morphology of lunar dust, any low-cost COTS sensors for lunar missions should be calibrated using aerosols with similar jagged grains (not spheres).

#### **A. Dust concentrations in spacecraft cabins and habitats**

The first instrument for monitoring suspended PM inside the ISS was the Airborne Particulate Monitor (APM), which was first deployed in Fall of 2020.<sup>40-41</sup> This reference-quality instrument operated in the US segment of the ISS and measured particle number concentrations in two separate size ranges of 5 nm to 3  $\mu\text{m}$  (fine) and 3-20  $\mu\text{m}$  (coarse). Low-cost sensors were deliberately avoided in this first experiment because the goal was to get the most accurate data on air quality, in terms of particles, before smaller, lower fidelity instruments were introduced. The results from the first deployments showed very dynamic fine fraction concentrations during crew work hours with intermittent spikes, but considering one-minute averages, PM counts during the day were typically less than 20 particles per  $\text{cm}^3$ . For the coarse fraction, the APM display consistently showed 0.0 particles/ $\text{cm}^3$  after less than a month of deployment, indicating that there is most likely an obstruction in the internal tubing which narrows to 0.8 mm. However, the data before the probable clog shows extremely low daily coarse fraction concentrations, less than one particle per  $\text{cm}^3$ , based on one-minute averages. These numbers are in contrast with nighttime when the crew is not active and particle concentrations drop to near zero because of the high ventilation and filtration rate on ISS.

Although it is not desirable, it is possible to convert a number concentration measured by APM to mass concentration,  $\text{mg}/\text{m}^3$ , the units of the maximum dust concentrations in NASA Standard 3001, Volume 2, Rev B.<sup>5</sup> This is strictly an exercise, to obtain an order-of-magnitude estimate and will not be performed on future data as a practice. A conservative extrapolation of APM fine fraction number concentration data is based on multiple assumptions which cannot be validated. First, all particles are assumed spherical, which is definitely not the case based on aerosol sample return from ISS.<sup>42-45</sup> The density of spacecraft cabin dust is unknown, but is assumed to be 2.5  $\text{g}/\text{cm}^3$ , about the same as Arizona Road Dust. It would be the most conservative approach to take the upper cut size limit, 3  $\mu\text{m}$ , as the assumed size of all the particles measured by APM. However, the virtual impactor inside the APM is not perfectly efficient, and therefore, 2.5  $\mu\text{m}$  would still be an extremely conservative assumption. That size conveniently corresponds to one portion of the ISS requirement, so this gross estimate conversion can be compared easily. Based on these assumptions for conversion, we look at the day of the highest peak measured in the US Lab in 2021, which was 102,217 particles/ $\text{cm}^3$ . This maximum was short-lived, with concentrations significantly reduced within 30 seconds. For that maximum (one data point), for one second, the highest mass concentration converts to approximately 3000  $\text{mg}/\text{m}^3$ , but the 24-hour average mass concentration during which that peak occurred would convert to 1.2  $\text{mg}/\text{m}^3$ . While APM was deployed in that ISS location, the average concentration over those 9 days converts to 0.67  $\text{mg}/\text{m}^3$ . While the highest number concentration spike ever recorded exceeds the NASA Std. 3001  $\text{PM}_{2.5}$  limit of 1  $\text{mg}/\text{m}^3$ , the 24-hour average gets close and the 9-day average mass concentration conversion is below the  $\text{PM}_{2.5}$  limit. A more common number concentration peak that typically occurs on weekends (observed from the APM measurements over many months) is on the order of 5,000 particles/ $\text{cm}^3$ , which is 20 times lower. Spikes of this nature are typically attributed to the crew performing vacuuming, for example, when racks are rotated or wall panels opened, a large amount of dust can be present and will be re-entrained into the air when disturbed by a vacuum cleaner nozzle.

The US segment of the ISS is equipped with high-efficiency particulate air (HEPA) filters that quickly remove particles nearly as fast as they are emitted, so the variability of the measured number concentration in a day can be extremely high. In this environment, low-cost sensors would be exposed to intermittent high and extremely low PM levels throughout a 24-hour period. This demonstrates the need for a high data sampling rate, ideally one data point every 10 seconds or less, which is typically not deemed necessary in Earth environmental monitoring (indoor or outdoor). Note that the ISS concentration scenario with intermittent spikes and near-zero concentrations during crew

sleep is drastically different from terrestrial indoor environments. Homes and workplaces do not have such a high filtration rate and therefore have more sustained concentrations (vs. spikes) and never have zero concentrations, even when unoccupied.

Low-cost COTS sensors often have concentration-dependent performance. Results of a study by Johnson et al. (2018) for monitoring PM<sub>2.5</sub> in different urban areas concluded that different model versions of low-cost PM<sub>2.5</sub> sensors from the same company had vastly different performance at different concentration levels, although they all had the same principle of operation.<sup>46</sup> Most models performed poorly below 40 µg/m<sup>3</sup> and others performed poorly above 280 µg/m<sup>3</sup>. None of the low-cost sensors tested were well-suited for 1-hour aerosol sampling of concentrations below 15 µg/m<sup>3</sup>. Kelly et al. (2016) evaluated the Plantower low-cost PM sensors (models PMS 1003/3003), which are nephelometers, and obtained drastically different results in the laboratory setup versus the field. While the concentrations recorded under controlled conditions within a wind tunnel correlated well with the gravimetric federal reference method for a wide range of high concentrations (200-850 µg/m<sup>3</sup>), it began reflecting non-linear responses at concentrations above 40 µg/m<sup>3</sup>.<sup>47</sup> Thus, the particle concentration ranges within a spacecraft cabin environment must be carefully considered and quantified, or estimated as accurately as possible, in advance of a mission. Any candidate particulate monitors must be tested with the expected concentration profiles, which may eliminate many COTS low-cost sensors.

On the Artemis missions, there will be two distinct concentration ranges for dust monitoring. In the orbiting vehicle, Gateway, the air will be very clean, similar to ISS, however, in the lunar lander, the concentrations of dust after an EVA may start extremely high and diminish as cleaning operations are carried out. Considering that most low-cost sensors typically measure a maximum concentration of 1 mg/m<sup>3</sup>, they will not be able to verify all the maximum concentration requirements in NASA Standard 3001, Volume 2, Rev B.<sup>5</sup> One possible solution is having two distinct instruments to cover the entire concentration range, from below 0.3 mg/m<sup>3</sup> to above 3 mg/m<sup>3</sup> accurately. In this scenario there is potential for low-cost sensors to be used, provided they are properly calibrated and tested. Besides covering the required mass concentration range, one could argue that a number concentration instrument capable of measuring down to the nanometer level would be extremely beneficial as well. The ultimate ideal instrument would be able to distinguish between different aerosol types, such as lunar dust, cabin dust, and smoke.

#### **IV. Dust Experiments Comparing an OEM Sensor and a Low-cost Sensor with a Reference Instrument**

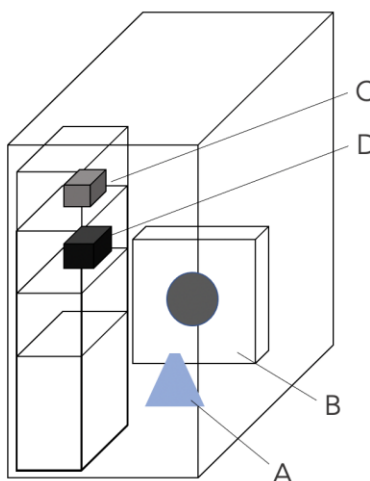
Most light-scattering aerosol instruments that measure mass concentration are calibrated with Arizona Road Dust (ARD), also known as ISO 12103-1 A1 test dust. This is a standard test dust that sufficiently represents many ambient aerosols on Earth, including jagged mineral dusts. The Artemis mission is expected to provide sample return of lunar dust, but for now, new lunar simulants have been created that are expected to represent the regolith at future landing sites. One simulant that mimics the lunar highlands dust is LHS-1D (the extra-fine variant consisting of particles ranging from 0.04 to 35 µm). Only one previous publication to date has documented testing low-cost sensors with lunar simulant. Vidwans et al. (2022) evaluated two different low-cost sensors with lunar simulant JSC-1a, and discussed potential deployment of these sensors in both the vacuum of the lunar surface (for EVAs) and in lander cabin environments.<sup>36</sup> Many more sensors should be tested with lunar simulant and evaluated based on the criteria and challenges outlined previously.

For instance, in this study, we have conducted chamber tests with a low-cost sensor called MODULAIR™-PM, comparing the response to both ARD and LHS-1D lunar simulant. This instrument uses both nephelometry and single particle scattering, combining an OEM Plantower (PMS5003) with an OEM OPC (Alphasense OPC-N3) in one system to improve ‘measurements’ (or estimates) of PM<sub>1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub>. The output from the nephelometer is combined with that from the OPC along with diameter-specific assumptions about the particle hygroscopicity and density to convert the raw sensor measurements to integrated mass concentration estimates. Aspiration efficiency is a factor in the conversion as well. The underlying theory and physics-based model used in the MODULAIR™-PM system is described in detail in the literature.<sup>34</sup> Both the raw OEM output and the converted data is available to the user, and the technique used to convert optical size distributions to mass concentrations is available in an open-source Python library (it was developed by the manufacturer to convert optical size distributions to mass concentrations for any size-resolving aerosol instrumentation).<sup>48</sup>

The goal of this proof-of-concept study is to demonstrate that one OEM sensor (Plantower) by itself does a very poor job at measuring  $PM_{10}$ . When this OEM unit is combined with a complementary OEM unit, and an intelligent physics-based model is used with known features of the aerosol being measured, the quality of the measurement is increased considerably. Here we show that the low-cost sensor can capture and characterize lunar simulants and terrestrial dust particle plumes with size distributions that extend beyond  $1\ \mu m$  in diameter. We also refute the claim that the OEM Plantower (PMS5003) nephelometer (which is inside the MODULAIR™-PM) can discriminate size-segregated mass concentrations.

The published specifications for the COTS low-cost sensor indicate that it can measure size-resolved mass concentrations ( $PM_1$ ,  $PM_{2.5}$ , and  $PM_{10}$ ) in the concentration range between 0 and  $2\ mg/m^3$  through the use of a physics-based model. The data inversion also provides particle size distributions ranging  $0.35\ \mu m$  to  $40.0\ \mu m$  in 24 bins. The operating conditions specify  $-20$  to  $60^\circ C$  and 5 to 95% RH and the waterproof plastic case is  $17 \times 17 \times 13\ cm^3$  ( $6.6 \times 6.6 \times 5.1$  cubic inches) weighing 1.8 kg (4 lb). Power needs are 5VDC 2A supply with 250 mA average consumption. This instrument has been deployed in many research campaigns<sup>49</sup> for up to 20 months including some high altitude locations ( $\sim 800$ -850 kPa). In these campaigns, no adverse particle sampling effects (inlet losses, particle beam focusing, flow) have been observed under lower pressure operating conditions. These early results are promising, however, testing COTS at relevant low pressures is necessary, and results may lead to changes in the data processing algorithm. Calibration interval for this device is not explicitly specified but based on 20 months performance in the field, it would reasonably be over a year, which is the expected interval for ISS life support items within this level of complexity.

The experimental setup consisted of a chamber  $1.8 \times 1.8 \times 1.2\ m^3$  ( $10' \times 6' \times 4'$  cubic feet) containing the MODULAIR™-PM and a reference instrument (GRIMM Model 11-D) shown schematically in Figure 1.

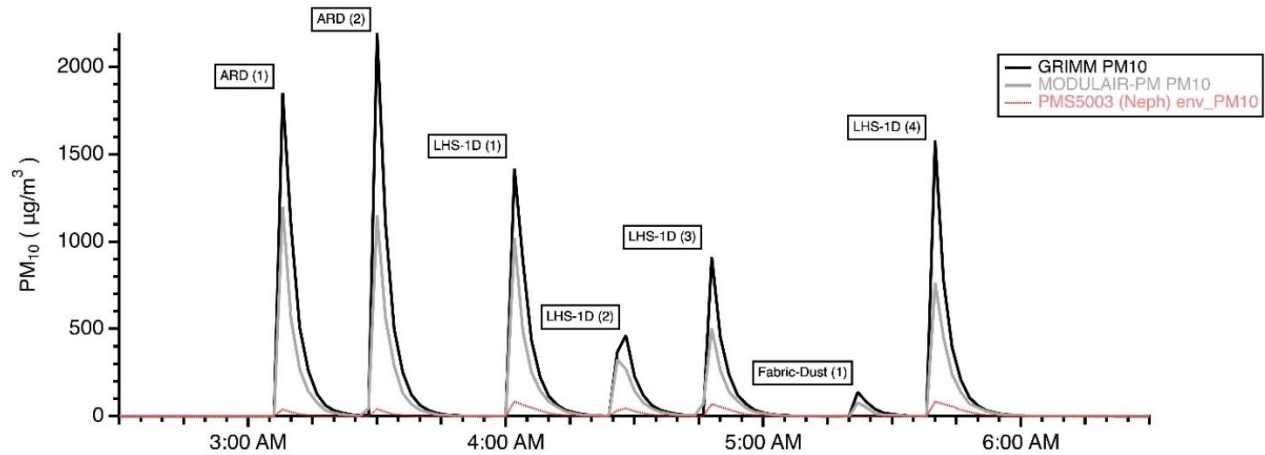


**Figure 1. The  $1.8 \times 1.8 \times 1.2\ m^3$  ( $10' \times 6' \times 4'$  ft<sup>3</sup>) experimental chamber used in the experiments. Components include (A) Dust Aerosol Generator, (B) Mixing Fan, (C) MODULAIR-PM Unit, (D) GRIMM-11-D.**

Particle charge was not quantified and relative humidity was not controlled during the experiments. The chamber included a mixing fan run continuously on low to provide well-mixed sampling conditions. In past experiments, multiple MODULAIR-PM systems positioned throughout the chamber volume (across the horizontal and vertical directions) confirm that the chamber environment is well-mixed over the timescale of the dust experiments shown here. Transient plumes of ARD and LHS-1D were introduced into the chamber via a pressure pulse of lab air through a 1/4" venturi nozzle attached to a sealed 50 mL volume containing the dust source. Multiple dust plume decay experiments were conducted for each type of dust.

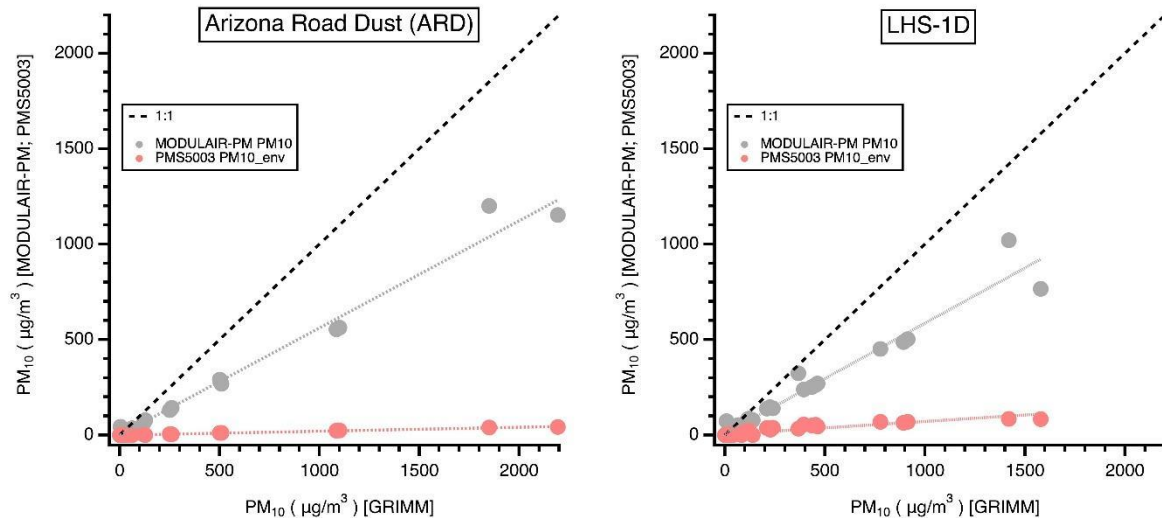
The  $PM_{10}$  response of the GRIMM, MODULAIR-PM, and OEM Plantower™ PMS5003 are shown in Figure 2. An additional  $PM_{10}$  transient experiment was conducted by vigorously shaking an article of clothing to simulate a typical fiber dust (lint) distribution in indoor settings from human movement. The data presented are 2-minute average concentrations from each device with transient  $PM_{10}$  plumes decaying to background levels over  $\sim 15$ -20 minute

timescales. The concentrations of the dust bursts were varied by changing the duration of the pressure pulse over the dust source from ~0.5 to 2 seconds.



**Figure 2. Time-series graph of chamber dust experiments comparing the PM<sub>10</sub> concentrations from MODULAIR-PM with the GRIMM-11D reference instrument and the OEM Plantower sensor (PMS5003).**

The data show that the low-cost COTS instrument closely tracks the evolution of each PM<sub>10</sub> plume as measured by the GRIMM-11-D reference instrument across peak concentrations from ~0.10 – 2.1 mg/m<sup>3</sup>. The PM<sub>10</sub> output from the Plantower PMS5003 itself is far less sensitive to the in-chamber PM<sub>10</sub> plumes. This illustrates one of the key disadvantages of relying on nephelometry alone, which is unable to detect particles larger than 1 μm in diameter. The OEM Plantower data output compares poorly to the reference instrument, however, when combined with another OEM sensor there is a ‘richer’ data set that can be exploited. If particle properties are known or can be estimated (size-dependent hygroscopicity, density) and attributes of the instrument are accounted for (size-dependent inlet losses [aspiration efficiency factors]), a data processing algorithm based on aerosol physics principles improves the measurement ability of the low-cost COTS sensor.



**Figure 3. Measurement correlation with ARD (left) and LHS-1D (right) for the low-cost COTS sensor and the OEM sensor.**

Figure 3 shows the correlation between the sensor derived PM<sub>10</sub> and reference PM<sub>10</sub> across the two dust sources tested in the chamber. Overall, low-cost COTS sensors exhibit similar sensitivity to ARD and LHS-1D, resulting from the comparable PSD of both dusts, similar refractive index, and morphology. This COTS sensor, as used in this experiment, is currently tuned for terrestrial indoor and outdoor aerosol measurements. It is expected that a physics-based model for spacecraft cabin aerosols can be created based on current knowledge of ISS PM. Similarly, the more information we get on lunar dust with the Artemis missions, the more likely a COTS low-cost sensor can be tuned for a lunar mission in which dust will be the main challenge.

## Conclusions

Practical aspects of aerosol monitoring aboard human spacecraft and outposts were reviewed and discussed along with features and pitfalls of COTS low-cost sensors currently available. A proof-of-concept experiment demonstrated that one OEM sensor (Plantower) by itself cannot measure PM<sub>10</sub>. Two complementary OEM units combined provide a richer data set that can be processed with an intelligent physics-based data processing algorithm that exploits known features of the aerosol being measured. The experiments show that this methodology increased the quality of the measurements by the low-cost COTS sensor considerably vs. the OEM sensor. The low-cost COTS sensor was able to characterize lunar simulant and terrestrial dust particle plumes with size distributions that extend beyond 1  $\mu\text{m}$  in diameter for concentrations up to 2.1 mg/m<sup>3</sup>.

The response of the low-cost COTS sensor was linear but lower in magnitude than that of the reference instrument; nevertheless, the physics-based model approach is adaptable for specific known aerosols that will be present in NASA missions. The OEM sensor by itself measured drastically lower peak concentrations and was unable to measure the fabric dust. Differences in response across the expected particle size spectrum and concentration ranges are critical factors in the performance of particulate monitors. At this point, the particle size range for lunar missions, as reflected in NASA's dust exposure requirements, must be covered by two different sensor technologies. Low-cost COTS sensors are attractive if they provide adequate and reliable data. Much more work lies ahead to identify, test and down-select sensors from a variety of sources using the methodology described.

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